

CP violation measurements at the LHCb experiment

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Decays of b-hadrons are the ideal place to perform measurements of CP violation. Many decay channels allow to over-constrain the unitarity triangles of the CKM matrix and test the SM hypothesis that a single phase is the origin of all CP violation. Charm decays also allow for tests of the SM. Recent results from LHCb are reviewed.

1. Introduction

CP violation was first observed by Cronin and Fitch¹ in 1964 in the kaon sector and is by now well established in the Standard Model (SM). The LHCb experiment is performing precision measurements in order to consolidate the consistency of the CKM picture and look for deviations from the CP Violation (CPV) expected in the SM. A selection of recent results from the LHCb experiment are presented. Where not explicitly stated all results are based on the analysis of 1 fb^{-1} of data collected in 2011 at a proton-proton collision energy of 7 TeV.

2. Measurement of the γ angle

One of the angles of the unitarity triangle is $\gamma = \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$. At the moment it has the weakest experimental constraints and therefore its measurement is an important test of the CKM consistency. LHCb expects to achieve a precision of 7° , after the analysis of the 3 fb^{-1} collected in 2011 and 2012 has been finished. The angle is measured using $B \rightarrow Dh$ decays, where h can be a pion or a kaon. In these decays γ arises from the interference of $b \rightarrow u$ and $b \rightarrow c$ transitions.

The measurement can be carried out using D decays in CP eigenstates KK and $\pi\pi$ (GLW method²), or also in $K\pi$ (ADS method³). In the latter case the $B^- \rightarrow D^0 K^-$ decay is colour favoured but the D^0 decay in $K^+\pi^-$ is CKM suppressed, yielding large interference. Combining the two methods and including also $D \rightarrow K_S hh$ decays the value of γ is measured to be $(62 \pm 12)^\circ$ ⁴. Most of the analysis included are on 1 fb^{-1} of data and being updated to 3 fb^{-1} .

3. B_s mixing and ϕ_s measurement

In the neutral B system, mixing is possible thanks to weak interaction box diagrams. The angle ϕ_s arises from the interference of B_s decays with and without mixing. The value of ϕ_s is well known in the SM, $\phi_s = -0.0364 \pm 0.0016 \text{ rad}$ ⁵, but New

Physics (NP) could add large phases. Here a measurement of ϕ_s is presented using $B_s \rightarrow J/\psi\pi\pi$ decays, which has recently been updated using 3 fb^{-1} of data⁶. ϕ_s is measured from a time-dependent amplitude analysis, namely fitting the decay-time distributions of B_s events that are flavour tagged at production. The fit considers the effect of a finite time resolution (40.3 fs in LHCb) and a decay-time dependent acceptance. The angle ϕ_s is measured to be $0.070 \pm 0.068(\text{stat}) \pm 0.008(\text{sys})$ rad. This is the single most precise measurement to date and it is in agreement with the SM. The measurement was also performed constraining the fit to zero CP violation and the value found is $0.075 \pm 0.065(\text{stat}) \pm 0.008(\text{sys})$ rad⁷.

4. Direct CP violation

In this section a few of the latest measurements of direct CPV at LHCb in the B and D sector are presented. In this type of analysis we look for a difference in the decay rates of charge conjugate decays.

$$A_{\text{raw}} = \frac{N(I \rightarrow f) - N(\bar{I} \rightarrow \bar{f})}{N(I \rightarrow f) + N(\bar{I} \rightarrow \bar{f})} \quad (1)$$

In general, the true CP asymmetry, A_{CP} , can be written as $A_{CP} = A_{\text{raw}} + A_{\text{det}} + A_{\text{prod}}$, where A_{det} is the bias due to a different detection efficiency for particles and antiparticles. This can be partly due to differences in performance in the left and right part of the detector and also to the fact that the nuclear interaction with the detector material is different for particles and antiparticles. To reduce the first effect LHCb's magnet polarity is periodically reversed so that left-right differences are averaged out. Finally, A_{prod} is the asymmetry arising from D or B meson production effects.

4.1. CP asymmetry in $B^0 \rightarrow \phi K^{*0}$

In this analysis the quantity $\Delta A_{CP} = A_{CP}(B^0 \rightarrow \phi K^{*0}) - A_{CP}(B^0 \rightarrow J/\psi K^{*0})$ is measured. The channel $J/\psi K^{*0}$, which has same final daughters as the signal, is used as a control channel in order to cancel detection and production asymmetries. The result is $\Delta A_{CP} = (1.5 \pm 3.2(\text{stat}) \pm 0.5(\text{sys}))\%$ ⁸.

4.2. 3-body charmless decays

$B^\pm \rightarrow \pi^- \pi^+ \pi^\pm$ and $B^\pm \rightarrow K^- K^+ \pi^\pm$ decays are analysed looking for direct CPV⁹. In a previous paper¹⁰ $B \rightarrow K^\pm \pi^- \pi^+$ and $B \rightarrow K^\pm K^- K^+$ were also considered. In this case the detection asymmetry of the pion is measured in LHCb using a tag-and-probe method. The detection asymmetry of kaons is measured using D decays to KK and $K\pi$ and correcting for the pion asymmetry. Finally, the production asymmetry is measured using $B^\pm \rightarrow J/\psi K^\pm$ decays, where the CP asymmetry is assumed to be zero, and correcting for the detection asymmetry of the kaon.

The results^{9 10} are:

$$\begin{aligned}
 A_{CP}(B^\pm \rightarrow K^\pm \pi^- \pi^+) &= 0.032 \pm 0.008(\text{stat}) \pm 0.004(\text{sys}) \pm 0.007 (J/K^\pm) \\
 A_{CP}(B^\pm \rightarrow K^\pm K^- K^+) &= -0.043 \pm 0.009(\text{stat}) \pm 0.003(\text{sys}) \pm 0.007 (J/K^\pm) \\
 A_{CP}(B^\pm \rightarrow \pi^\pm K^- K^+) &= -0.141 \pm 0.040(\text{stat}) \pm 0.0018(\text{sys}) \pm 0.007 (J/K^\pm) \\
 A_{CP}(B^\pm \rightarrow \pi^\pm \pi^- \pi^+) &= 0.117 \pm 0.021(\text{stat}) \pm 0.009(\text{sys}) \pm 0.007 (J/K^\pm)
 \end{aligned}$$

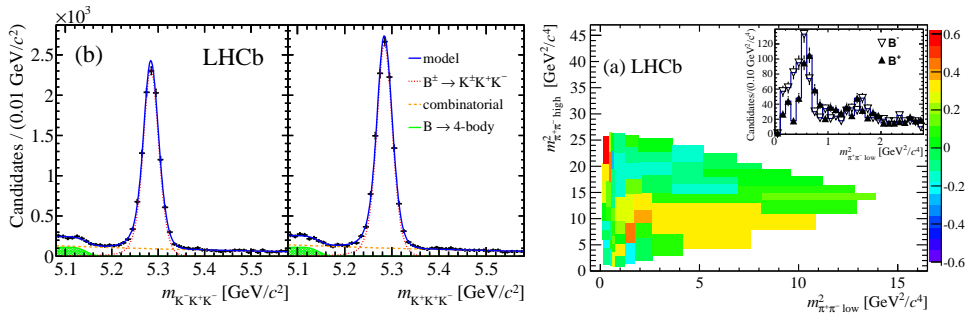


Fig. 1. Invariant masses of $K^+K^+K^-$ and $K^-K^+K^-$ systems (left) and raw asymmetries in the $B^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ Dalitz plot (right).

The significance of $A_{CP}(B^\pm \rightarrow K^\pm K^+ K^-)$ exceeds three standard deviations, yielding the first evidence of a CP asymmetry in charmless three-body decays. Figure 1 (left) shows $K^+K^+K^-$ and $K^-K^+K^-$ invariant masses. The Dalitz plots were also studied, looking for localised asymmetries. Figure 1 (right) shows asymmetries in the raw number of events in bins of the Dalitz plot for $B^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ decays. Large asymmetries are clearly visible in the localised region of phase space defined by $m_{\pi^+ \pi^-}^2 > 15 \text{ GeV}^2/c^4$ and $m_{\pi^+ \pi^-}^2 < 0.4 \text{ GeV}^2/c^4$, where no significant contributions from resonances are expected.

4.3. CP asymmetry in $\Lambda_b \rightarrow J/\psi p \pi^-$

In this analysis the ΔA_{CP} between the Cabibbo suppressed (CS) $\Lambda_b \rightarrow J/\psi p \pi^-$ and Cabibbo favoured (CF) $\Lambda_b \rightarrow J/\psi p K^-$ is measured. The data sample is split in two exclusive samples using the particle ID information on the meson in the final state. In Fig. 2 invariant masses for the two samples are reported. The production asymmetry is the same for the two channels and cancels in the difference. Therefore $\Delta A_{CP} = A_{CP}(p\pi) - A_{CP}(pK) + A_{det}(\pi) - A_{det}(K)$. The detection asymmetries of kaon and pion can be determined using the $B^0 \rightarrow J/\psi K^{*0}$ decay, where the CP asymmetry is assumed to be zero and the production asymmetry is measured to be consistent with zero¹¹, giving $A_{CP}(B^0 \rightarrow J/\psi K^{*0}) = A_{det}(\pi) - A_{det}(K)$. The result, using 3 fb^{-1} of data, is $\Delta A_{CP} = (5.7 \pm 2.3 \pm 1.2)\%$ with a 2.2σ deviation from zero¹².

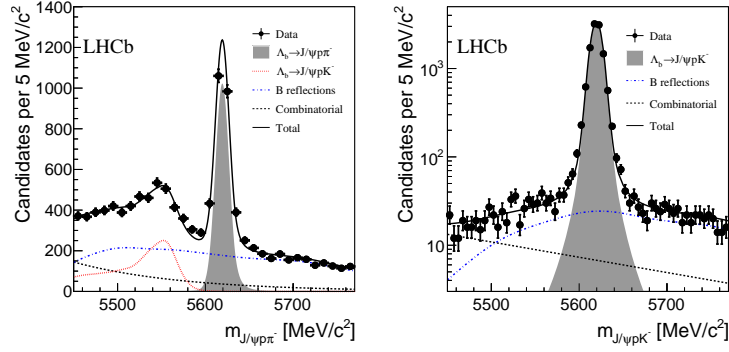


Fig. 2. Invariant masses of the $J/\psi p \pi^-$ (left) and $J/\psi p K^-$ (right) systems.

4.4. Direct CPV in $D^0 \rightarrow h^+ h^-$

This analysis uses D^0 decays in CP eigenstates (KK and $\pi\pi$). The D flavour is tagged at production by looking at the charge of the muon in the decay $B \rightarrow D\mu\nu X$. These are Cabibbo suppressed decays where penguin diagrams may contribute allowing space for New Physics. Furthermore, using charm decays, we have $O(10^6)$ events available, a factor 1000 more than B decays, which allows more precise measurements. The asymmetry is expected to be equal in magnitude and opposite in sign so the quantity measured is the A_{CP} difference $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$, where detection and production asymmetries cancel. On 3 fb^{-1} of data, this is measured to be $0.14 \pm 0.16(\text{stat}) \pm 0.08(\text{sys})$, in agreement with the SM¹³.

4.5. Direct CPV in $D^+ \rightarrow \pi^- \pi^+ \pi^+$

In this analysis the Dalitz plot of the Cabibbo suppressed $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decay is studied, looking for local CPV. The analysis is performed by dividing the Dalitz plot into bins and calculating in each bin a significance function defined as:

$$S_i \equiv \frac{N_i(D^+) - \alpha N_i(D^-)}{\sqrt{\alpha(N_i(D^+) + N_i(D^-))}}, \quad (2)$$

where $\alpha = \sum N_i(D^+) / \sum N_i(D^-) = 0.992 \pm 0.001$ accounts for global asymmetries. Figure 3 shows the significances in the Dalitz plot and how the values are distributed. If there is no local CPV the significances should follow a Gaussian distribution. Finally, a χ^2 test is used to find a p-value for the non-CPV hypothesis. No local CPV is found¹⁴.

5. Conclusions

The most recent combination of the CKM angle γ measurements at LHCb was presented, where the value found is $(62 \pm 12)^\circ$. A number of results of CPV searches in B_s mixing and decay rates were also performed where in general a good agreement with the SM is found. No evidence for CPV in charm decays is found.

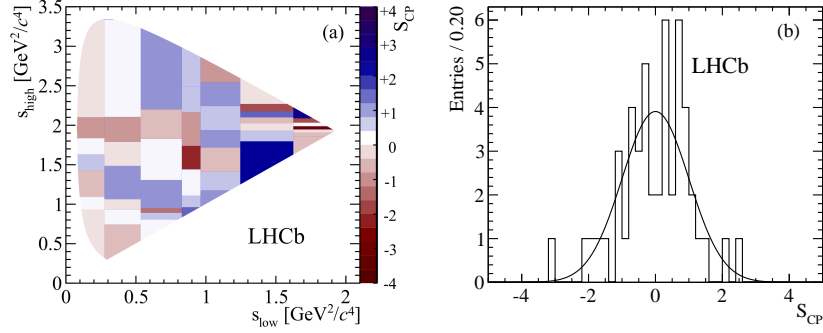


Fig. 3. Significances in the Dalitz plot (left) and their distribution (right).

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